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Evidence for $H \rightarrow \mu\mu$ with CMS Run II Data and Projected Sensitivity at the HL-LHC

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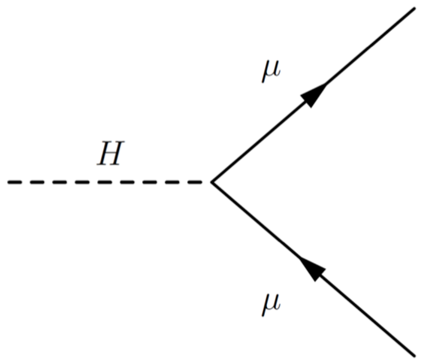
Motivation of $H \to \mu\mu$

- Since the Higgs discovery in 2012, CMS and ATLAS have measured Higgs mass, width, couplings, and CP properties with steadily improving precision.
- Higgs boson couplings to gauge bosons and third generation fermions were established.
- Next frontier: Probe Higgs couplings to second generation fermion via $H \to \mu\mu$.

- Experimentally challenging search:
  - Relatively rare decay mode:

$$\mathcal{B}(\mathrm{H} \to \mu^+\mu^-) = 2.18 \times 10^{-4}$$



  - Very large DY background ⇒ very small S/B with inclusive selections.

Run-II Analysis

- CMS Run-II datasets: 137 fb^{-1} of 13 TeV pp collisions

Events with two prompt, isolated, and oppositely charged muons

ttH channel

- Phase-space containing at least **one medium** or two **loose b-tagged** jets
- Based on the presence of addition leptons (μ,e)

→ ***ttH hadronic*** / ***ttH leptonic***

VH channel

- Targeting **leptonic decays** of W/Z
- Veto events with b-jets already belonging to the ttH channel

→ ***WH leptonic*** → 3μ or 2μ1e final states

→ ***ZH leptonic*** → 4μ or 2μ2e final states

VBF channel

- Veto ttH events
- Veto VH events
- Select events with two jets with **VBF-like kinematics**

$p_T^{j1} > 35\ GeV$

$p_T^{j2} > 25\ GeV$

$m_{jj} > 400\ GeV$

$|\Delta\eta_{jj}| > 2.5$

ggH channel

- Collects all the events not selected by the other channels
- Phase-space dominated by events with zero or one additional jet and no extra leptons apart from the H(μμ) candidate

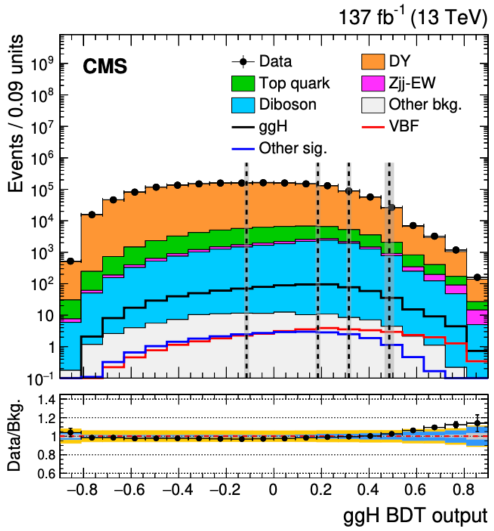
- Signal is extracted with a **simultaneous fit** across all categories to observables chosen for each category.

Run-II Analysis --- ggH

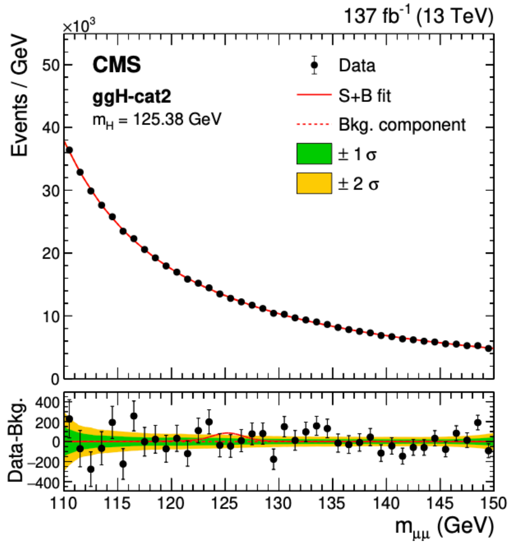
- Phase space dominated by 0–1 jet events with only the μμ pair and multi-jet events are kept if not VBF-like.

- **Analysis Strategy**
  - Extract the signal by **fitting dimuon invariant mass**
    - Signal: sharp peak at 125 GeV; Background: smooth, falling distribution

    → Enables data-driven background estimation via analytical fit



- BDT used to separate Higgs signals from expected backgrounds
- Divide event in categories characterized by different S/B



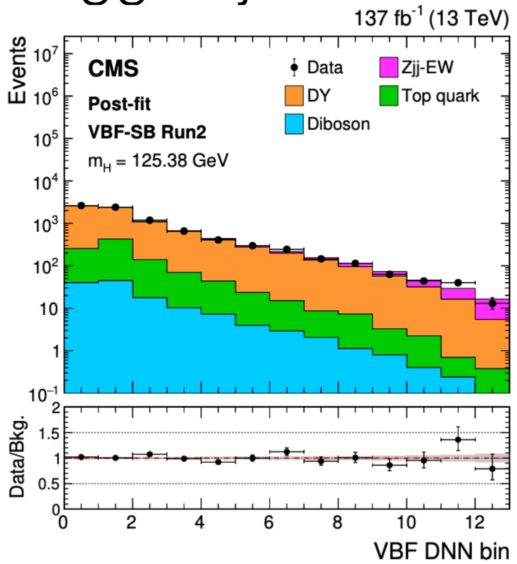
$$B_{cat}(m_{\mu\mu}, \vec{\alpha}, \vec{\beta}) = N_B \times F_{core}(m_{\mu\mu}, \vec{\alpha}) \times T_{SMF}(m_{\mu\mu}, \vec{\beta})$$

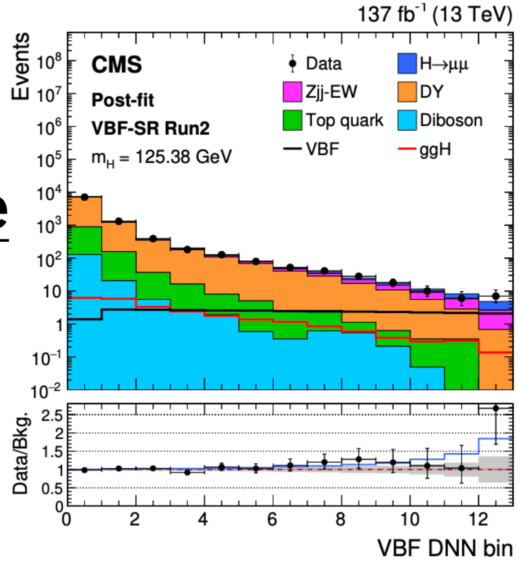
- Signal model: m(μμ) described with a Double Crystal-ball function.
- Background modeling: Core-PDF method
- Core background function built as discrete profile of two physics-inspired (Breit-Wigner, FEWZ) and an agnostic (sum of exponentials) function.

Run-II Analysis --- VBF

- Select the events with neither additional charged leptons nor b-tagged jets and a pair of jets with large mjj and Δηjj

- **Analysis Strategy**
  - Signal extraction is fully based on MC
    - Low signal event statistic
    - Reliable background modeling (DY+jets, VBF Z)
  - Train a DNN to distinguish signal from background including the dimuon mass as input.
  - VBF H→μμ signal is extracted by **fitting DNN output score** in data directly to background shape predictions from simulation



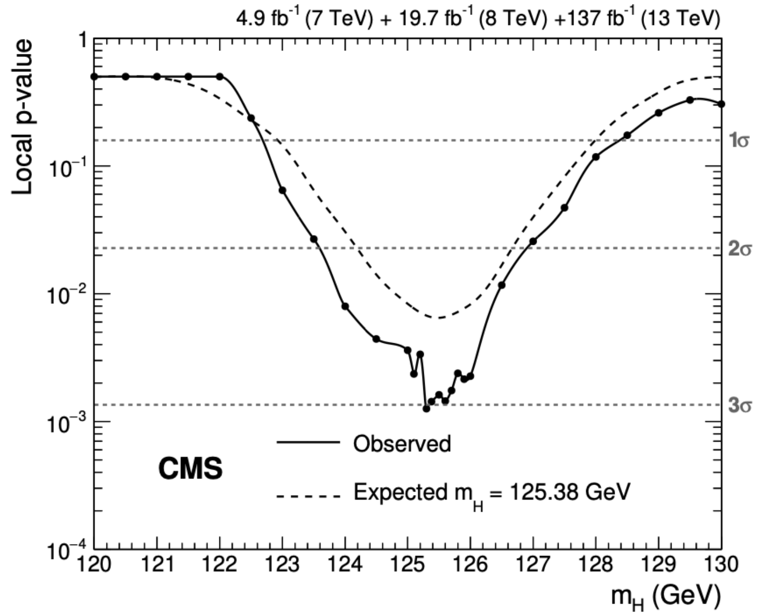


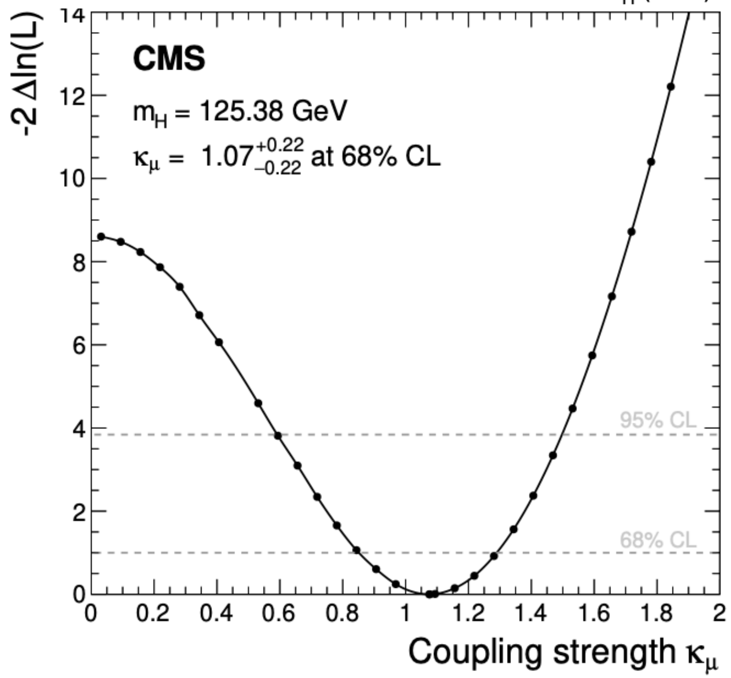
Run-II Analysis --- Results

- Measurement of H→μμ combines four separate analyses targeting ggH, VBF, VH, and ttH production.
- Final results are obtained from combination with CMS Run-1 H→μμ search.
- Measured signal strength

$$\mu = 1.19^{+0.40}_{-0.39}(\text{stat})^{+0.15}_{-0.14}(\text{syst})$$

- Observed (expected) significance is 2.98σ (2.48σ).
- Higgs coupling to muons relative to SM Kμ is constrained at 95% CL to [0.59, 1.50].
- **Observe evidence for Higgs boson decay to muons.**

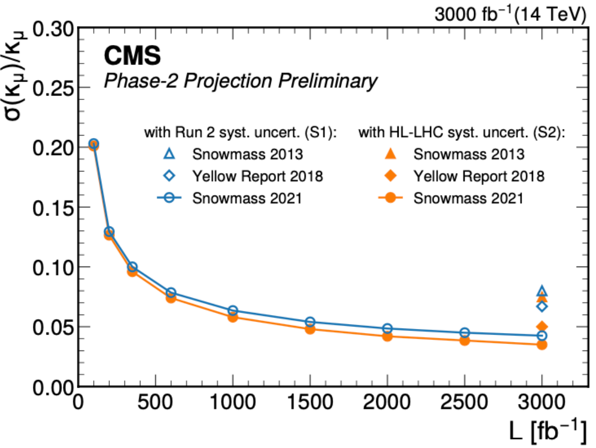




HL-LHC Prospects: Higgs → μμ Decay

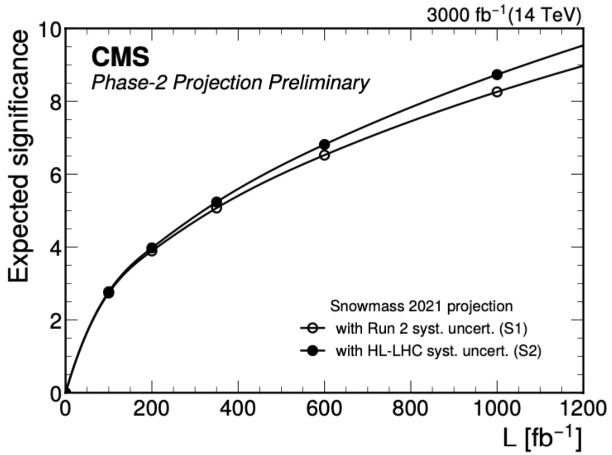
- **HL-LHC & Detector Upgrades**
  - HL-LHC conditions: $\sqrt{s}$ = 14 TeV, $\mathcal{L}$ up to 3 ab^{-1}
  - CMS Phase-2 upgrades -> ~30% improved dimuon mass resolution

- **HL-LHC Extrapolation Strategy**
  - Use Run-2 H→μμ analysis Strategy
  - Extrapolate yields to $\sqrt{s}$ = 14 TeV and 3 ab^{-1}; include cross-section changes and acceptance gains.
  - Two uncertainty scenarios considered:
    - S1: systematic uncertainties stay like Run-2.
    - S2: experimental systematics scale down with $\sqrt{\mathcal{L}}$ (until some floor), theoretical uncertainties halved.



HL-LHC Projection Results

- HL-LHC (3 ab^{-1}):
  - Signal strength uncertainty: ~8.5% (S1), ~7.0% (S2)
  - K_{μ} uncertainty: ~4.3% (S1), ~3.5% (S2).
- With only 14 TeV data, 5σ significance could be be achieved with $\mathcal{L} \simeq$ 300-350 fb^{-1}.



HL-LHC will make it possible to measure Higgs–muon coupling with high precision.

Summary and Plan

- First experimental evidence of $H \rightarrow \mu\mu$ decay.
- Observed significance: 3σ with CMS Run-2 dataset (13 TeV, 137 fb^{-1}).
- Results consistent with the Standard Model Higgs–muon Yukawa coupling.
- Run-3 analysis ongoing, aiming for improved precision and potential discovery.
- HL-LHC era will enable precision Higgs flavor physics, probing Yukawa couplings at the few-percent level.

Thanks a lot for your attention!